

# Life cycle assessment of construction materials: the influence of assumptions in end-of-life modelling

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## Abstract

**Purpose** The nature of end-of-life (EoL) processes is highly uncertain for constructions built today. This uncertainty is often neglected in life cycle assessments (LCAs) of construction materials. This paper tests how EoL assumptions influence LCA comparisons of two alternative roof construction elements: glue-laminated wooden beams and steel frames. The assumptions tested include the type of technology and the use of attributional or consequential modelling approaches.

**Methods** The study covers impact categories often considered in the construction industry: total and non-renewable primary energy demand, water depletion, global warming, eutrophication and photo-chemical oxidant creation. The following elements of the EoL processes are tested: energy source used in demolition, fuel type used for transportation to the disposal site, means of disposal and method for handling allocation problems of the EoL modelling. Two assumptions regarding technology development are tested: no development from today's technologies and that today's low-impact technologies have become representative for the average future technologies. For allocating environmental impacts of the waste handling to by-products (heat or recycled material), an attributional cut-off approach is compared with a consequential substitution approach. A scenario excluding all EoL processes is also considered.

**Results and discussion** In all comparable scenarios, glulam beams have clear environmental benefits compared to steel frames, except for in a scenario in which steel frames are recycled and today's average steel production is substituted, in which impacts are similar. The choice of methodological approach (attributional, consequential or fully disregarding EoL processes) does not seem to influence the relative performance of the compared construction elements. In absolute terms, four factors are shown to be critical for the results: whether EoL phases are considered at all, whether recycling or incineration is assumed in the disposal of glulam beams, whether a consequential or attributional approach is used in modelling the disposal processes and whether today's average technology or a low-impact technology is assumed for the substituted technology.

**Conclusions** The results suggest that EoL assumptions can be highly important for LCA comparisons of construction materials, particularly in absolute terms. Therefore, we recommend that EoL uncertainties are taken into consideration in any LCA of long-lived products. For the studied product type, LCA practitioners should particularly consider EoL assumptions regarding the means of disposal, the expected technology development of disposal processes and any substituted technology and the choice between attributional and consequential approaches.

**Keywords** Attributional · Consequential · Construction product · Disposal · LCA · Long-lived product · Infrastructure · Waste management

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## 1 Introduction

For long-lived products manufactured today, end-of-life (EoL) processes such as demolition and disposal will take place in a distant future. For construction materials, EoL processes are often estimated to take place in 50–100 years (Frijia et al. 2011). Due to technological change, the nature of such processes is highly uncertain. This time-dependent

uncertainty has previously been acknowledged as a challenge typical for life cycle assessments (LCAs) in the construction industry (Singh et al. 2011; Verbeeck and Hens 2007). This uncertainty is nevertheless often neglected in LCAs of constructions and construction materials, and EoL practices of today are assumed to be valid without any explicit explanation, even when the aim is to support decisions concerning contemporary constructions that are expected to stand for a long time (e.g. Bribián et al. 2011; Habert et al. 2012; Lundie et al. 2004; Persson et al. 2006). There are exceptions; for example, Bouhaya et al. (2009) set up scenarios to account for different possible future means of EoL treatment of a bridge.

To consider EoL uncertainties is especially important when EoL practices may significantly influence the environmental impact. For buildings, efficient recycling at the disposal stage may save energy that corresponds to 29 % of the energy use in manufacturing and transportation of the construction materials (Blengini 2009). Moreover, energy savings from efficient recycling may correspond to 15 % of the total energy use of a building's life cycle (Thormark 2002). Although a building's use phase is often said to contribute 70–90 % of its environmental impact (Beccali et al. 2013; Cuéllar-Franca and Azapagic 2012; Ortiz et al. 2010), the relative importance of EoL processes is now rising due to increasingly energy-efficient buildings (Dixit et al. 2012); it has even been argued that poorly defined functional units often lead to exaggerated data on energy usage in the use phase (Frijia et al. 2011). The environmental impact of the waste handling of construction materials is also considered significant simply because of the sheer amount of such materials existing in society (Bribián et al. 2011; Singh et al. 2011; Blengini 2009). Finally, it has been shown that assumptions on EoL modelling can be of great importance for the life cycle impact of construction materials (Ardente et al. 2008).

So there are strong reasons to improve the modelling of EoL processes in LCAs of construction materials. This can contribute to more robust decision making in the construction sector, for example, in the development of new construction materials and policies.

#### 1.1 First aim: to test how EoL assumptions influence LCA comparisons of different construction materials

In the present paper, we use LCA to compare the environmental impact of alternative internal roof constructions for an industrial hall: glue-laminated (glulam) wooden beams and steel frames. The geographical scope is Europe, thus the product systems are modelled for European average conditions. A temporal dimension is introduced in the mapping of the product system, which contrasts with the traditional LCA practice of assuming time-invariant product systems. This is done by distinguishing between processes occurring today or

in a near future and processes occurring in a distant future, such as EoL processes, as these are inevitably subject to larger uncertainties. Due to these uncertainties, a range of scenarios are set up to test how assumptions regarding EoL processes influence the LCA results.

#### 1.2 Second aim: to compare the influence of attributional and consequential approaches to EoL modelling

The second aim concerns the influence of a specific assumption in EoL modelling: the choice between an attributional and a consequential approach. A consequential approach is increasingly used in LCAs but often in an inconsistent manner. Even LCA standards and handbooks (e.g. BSI 2011; WBCSD/WRI 2011; European Commission 2010) permit the use of consequential elements (e.g. substitution as a means of avoiding allocation) in attributional LCAs. This has been criticised as leading to results with unclear meaning (Brander and Wylie 2012). There is clearly a need for research on how to choose between different LCA approaches, how to apply the chosen approach consistently and in what contexts the choice matters. This paper aims at contributing to this research, by comparing attributional and consequential approaches for modelling the EoL processes of construction materials.

## 2 Methods

LCA was used because it is a well-developed and increasingly popular method (Peters 2009) for assessing the environmental impact of products. We used the LCA software GaBi 5 (PE International 2013) and selected a subset of the environmental impacts and resource use parameters recommended in EN 15804, the standard for environmental product declarations of construction products (SIS 2012): total and non-renewable primary energy demand (PE), water depletion potential, global warming potential (GWP), eutrophication potential (EP) and photo-chemical oxidant creation potential (POCP). A subset of the impact categories recommended in EN 15804 was deemed sufficient for the purpose of this paper, but for a comprehensive comparison of building elements, all recommended impact categories should be considered along with other relevant impact categories (as discussed in section 5).

The applied total PE indicator accounts for all energy extracted from the earth, including renewable energy and the energy content of any material and fuel inputs. This indicator reflects a concern about limited availability of energy resources in society. The non-renewable PE indicator focuses on the exhaustibility and limited access to fossil energy sources (Arvidsson et al. 2012). Water depletion potential is the name given to the water use impact category in the ReCiPe framework (Goedkoop et al. 2012); this is a basic volumetric

proxy for the burden on the environment and resources caused by water use. More comprehensive approaches exist (see Kounina et al. 2013), but for accuracy, they require detailed information about the location of the water being used (Sandin et al. 2013). GWP, EP and POCP are commonly studied impact categories in the construction sector with established characterisation methods. For characterisation, we used the CML 2001 framework (Guinée et al. 2002), with factors updated in 2010; thus GWP calculations include carbon sequestered in the product and considers biogenic carbon dioxide emissions as climate neutral (how to account for sequestration and temporal storage of carbon is a topic of debate—see Brandão et al. 2013).

To properly provide understanding of methodological choices regarding system boundaries and choice of data type, there is a need to elaborate on where the present study is positioned on the attributional-consequential spectrum. Although the influence of both attributional and consequential approaches is explored in the EoL scenarios, we would call the overall study primarily consequential. This is because the aim of the comparison is to support more robust decision making. For this reason, we study the consequences of choosing one of two engineering alternatives, in other words, the consequences of increased production of either alternative. The choice of a consequential approach is manifested primarily in the choices of system boundaries: we exclude processes that are assumed to result in identical impacts for the compared product systems. The use of average European data could, on the other hand, be viewed as adhering to an attributional tradition, but this is suitable as we are studying the average European consequence of choosing either of two alternative products. In practice, the consequence of choosing between alternative construction materials will depend on which European country (or even in which part of a country) the materials are produced, used and disposed of, and in each such case, the choice between average and marginal data may significantly influence the LCA results. It is not within the scope of this study to explore such micro-level consequential effects, and European average data is thus deemed the most suitable data to use. Besides, some authors have suggested that in markets constrained by regulation (e.g. national biodiversity conservation policies), the marginal supply should be defined as the planned/predicted supply rather than the uninstalled technology with the lowest long-term marginal cost (Schmidt et al. 2011). At the European level, even extrapolation from current average supplies could thus be a better estimate for the marginal supply than the uninstalled supply with lowest long-term marginal cost. Nonetheless, in some of the EoL scenarios, data on a single technology is used in what can be called “cornerstone” (Lundie et al. 2004; Pesonen et al. 2000) or “explorative” (Börjesson et al. 2005) scenarios—these should not be seen as marginal technology scenarios but as a means of exploring the possible range of

future states by assuming a single technology to be representative for the average technology.

The consequential approach is also present when substitution is applied to avoid allocation in the disposal stage. This means that by-products of the disposal process are assumed to substitute a product manufactured by alternative means and that the environmental impacts thereby avoided are credited to the system under study. In EoL scenarios with incineration as the assumed means of disposal, the by-product is assumed to be heat, and the substituted means of heat production is assumed to be combustion of natural gas or municipal biowaste (food and gardening waste with a water content of 60 wt% (Jungbluth et al. 2007)). In EoL scenarios with recycling as the assumed means of disposal, the by-product is the recycled material (wood and steel, respectively), and when substitution is applied, the substituted means of material production is assumed to be the current average European production (for wood: round wood, for steel: a mix of production from primary and recycled steel) or, in one EoL scenario for steel frames, production from recycled steel only.

In other EoL scenarios, the cut-off method is applied to allocate the environmental impacts between the roof construction and the by-products of the disposal process, which means that only impacts directly caused by a product are allocated to that product. This is a common allocation method in LCA of open recycling systems and thus a common method in LCAs of construction materials. In our case, impacts from manufacturing, use and disposal of the roof construction are allocated to it, and impacts from the subsequent life cycle processes of the by-products (e.g. reprocessing and final disposal of the recycled materials) are allocated to those processes and thus cut-off from the studied system. This approach can be seen as attributional, as it does not account for consequences in the surrounding market. It is the use of different approaches when modelling the EoL scenarios that enables the second aim of the paper to be fulfilled: the comparison of attributional and consequential modelling approaches.

### 3 System descriptions

The functional unit (FU) is defined as the internal roof construction necessary to support a 90-m<sup>2</sup> roof for an industrial hall—a typical area supported by one glulam beam or one steel frame. A simple and typical construction for an industrial hall was chosen: a single, sloping roof with a 1:10 inclination and an aluminium roof cover. We assume a full service-life to be 50 years for both constructions.

It is reasonable to assume that the choice of roof cover and materials in other parts of the building does not vary depending on the internal roof construction; therefore, these parts of the building are excluded from the study. Also, impacts from the construction phase is disregarded, as data in Björklund and

Tillman (1997) and Björklund et al. (1996) show identical energy use for the installation of wood and steel frame structures, and energy use can be assumed to be the main driver for impacts from the installation phase. Maintenance is normally not required for internal roof structures, and therefore we assume maintenance-free structures. Figure 1 shows a flowchart of the main processes of the studied systems.

### 3.1 Process descriptions

Due to a lack of up-to-date European data, inventory data on glulam beam manufacturing in the US Pacific Northwest is used (Puettmann et al. 2013). Manufacturing includes drying of green lumber, grading of lumber, end jointing the lumber into longer laminations, face bonding the laminations together with resin, finishing and fabrication. The inputs (except glue) and emissions are allocated between beams and by-products (shavings and trimmings) on a mass basis. We assume that no surface treatment is applied after installation, as this is usually not required for internal roof structures (personal communication with Mats Axelsson, SP Technical Research Institute of Sweden, February 2012).

Manufacturing of the steel frame includes cutting, bending, welding and drilling of steel sheets (Björklund et al. 1996). Often, the steel frame is coated with a primer and possibly also a top coating. However, in principal, a coating is not needed for an interior steel frame; therefore, it is omitted in this study, which is consistent with previous studies (e.g. Björklund et al. 1996).

At the end of the service life, glulam beams are usually recovered and used for new applications, or incinerated, often as fuel for district heating systems (Carling 2008; Björklund and Tillman 1997). These two disposal methods are studied in the different EoL scenarios. The glue is assumed not to give rise to more hazardous emissions in the incineration than wood does (Erlandsson 2007). Steel is typically recovered from building sites and used for production of recycled steel (Björklund et al. 1996), thus recycling is the disposal method studied in the EoL scenarios. The EoL scenarios are further described in section 3.2.

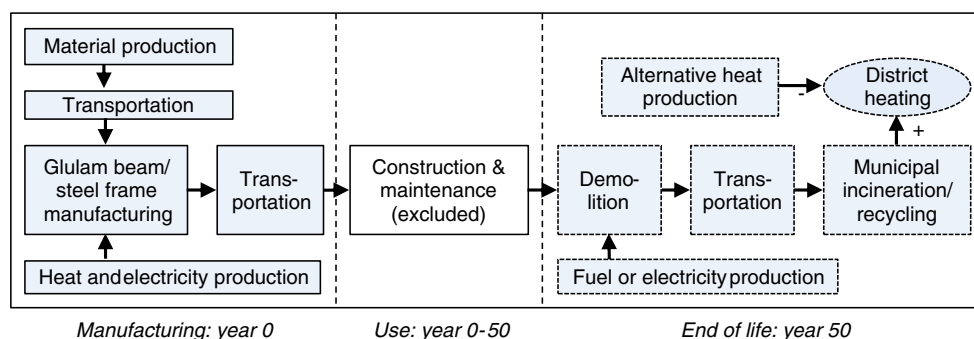
Table 1 shows inventory data. For all processes, inventory data representative for European conditions is used. References and further descriptions of all inventory datasets can be found in Table S1 of the Electronic Supplementary Material.

### 3.2 End-of-life scenarios

The EoL scenarios are described in detail in Table 2. Assumptions regarding the following features of the EoL processes are tested: energy source used in demolition, fuel type used for transportation to the disposal site, means of disposal and method for handling the allocation of environmental impacts to by-products of the disposal. Two assumptions regarding technology development are tested: no development from today's technologies and that today's low-impact technologies have become representative for the average future technologies (for these scenarios, the prefix "green" is used in the scenario abbreviations). In "green" scenarios, wind power is assumed to replace diesel as the energy source in demolition, EoL transportation is assumed to run on rape methyl ester (RME) biodiesel instead of today's European fleet average fuel (low-sulphur diesel), and in scenarios where substitution is applied, a low-impact technology is assumed to be substituted. "Inc" and "Re" in the abbreviations refer to the means of disposal (incineration or recycling), and "Cut" and "Sub" refers to the method for handling allocation problems (cut-off or substitution).

The average technology in 50 years can of course have lower impacts than today's low-impact technology, but to account for this would require inventory data which is not available at present time. However, the "NoEoL" scenarios—in which all EoL processes are excluded—can be seen as "green extremes": environmental impacts of future processes are considerably lower than of today's and thus ignored. These scenarios are also reasonable if it is argued that rapid reduction of current levels of environmental impact is urgent and impacts occurring in 50 years should be subject to a high discount rate, which eliminates them from consideration. The three assumptions regarding future technology—today's average technology, today's low-impact technology and fully

**Fig. 1** Process flowchart for glulam beam and steel frame life cycles. Processes in boxes with dashed lines are modelled differently in the various EoL scenarios



**Table 1** Inventory data for the glulam beam and steel frame product systems

Processes	Amount	Unit
Reference flow: glulam beam	1,280	kg
Glulam beam manufacturing		
Sawn softwood timber, rough, kiln dried	959	kg
Sawn softwood timber, rough, green	322	kg
Liquefied petroleum gas	3.50	L
Gasoline	46.2	L
Diesel	0.95	L
Glue (PVAc)	21.4	kg
Natural gas	10.5	m <sup>3</sup>
Electricity (continental European mix)	183	kWh
Wood fuel	49.7	kg
Polyethylene (for packaging in transportation)	8.34	kg
Demolition, energy (diesel or wind)	225	MJ
Disposal by municipal incineration (by-product: heat, substitutes natural gas or municipal biowaste)	20,480	MJ
Disposal by recycling (by-product: wood, substitutes debarked round wood)	1,280	kg
Reference flow: steel frame	1,270	kg
Steel frame manufacturing		
Electricity	2,540	MJ
Steel (low-alloyed)	1,270	kg
Demolition, energy (diesel or wind)	229	MJ
Disposal by recycling (by product: steel, substitutes average low-alloyed steel or recycled un- and low-alloyed steel)	1,270	kg
Transportation of input materials: 20–28 t lorry (fleet average)	200	km
Transportation to building site: 20–28 t lorry (fleet average)	500	km
Transportation to disposal site: 20–28 t lorry (fleet average or RME)	50	km

disregarding any impact from future technology—can be seen as a sensitivity analysis of the inventory data for the EoL processes.

#### 4 Results

Figure 2 shows the results of the impact assessment (numeric results can also be found in Table S2 of the Electronic Supplementary Material). In all scenarios, the glulam beam exhibits lower GWP, irrespective of whether an attributional, a consequential or an EoL exclusion approach is applied, although magnitudes differ considerably. Green scenarios show notably higher GWP in the substitution scenarios; this is because the substituted EoL treatment technology is cleaner, resulting in lower avoided impacts. The negative GWP in glulam manufacturing is due to the carbon withdrawn from

the atmosphere during forest growth and the subsequent storage of carbon in the glulam beam.

For EP, the main difference from GWP can be seen when comparing scenarios IncSub and GreenIncSub; more nitrifying emissions are avoided if heat from municipal biowaste is substituted compared to heat from natural gas. POCP results are similar to EP results, except for that it matters less what technology is assumed to be avoided in the consequential glulam beam scenarios with incineration as the means of disposal (compare scenarios IncSub and GreenIncSub).

The method for calculation of water depletion potential excludes natural rainfall as an input to production, which is seen clearly in the low water depletion potential for glulam beams. This is the simplest consequential approach—considering rain as an input that is independent of production rate (see, e.g. Peters et al. 2010). The high water depletion potential for the steel frames originates mainly from iron ore mining for production of primary steel: compare steel frame scenarios ReSub, in which we assume that the recycled steel substitutes European average (mix of primary and recycled) steel production, and GreenReSub, in which we assume that it substitutes steel production from recycled steel only. In one sense, all scenarios are attributional in terms of the response of hydrological systems to forestry. If one instead considers the consequences of forest harvesting on the hydrological behaviour of forest soils (e.g. increased runoff after harvesting—see Sandin et al. 2013), one could estimate a hydrological consequential version of each of the scenarios, which would influence the impact assessment of water use.

Total PE is the indicator where glulam beam and steel frame scenarios overall are most similar, while there are considerable differences in terms of non-renewable PE. The reason for the negative non-renewable PE score in glulam beam scenario IncSub is the substitution of natural gas. Furthermore, the high total PE of the glulam beam scenario GreenIncSub is because the substituted energy source is a municipal biowaste, which—as it is a waste product—is not allocated any PE during production.

#### 5 Discussion and conclusions

Despite our initial concern that the results of this comparative LCA might be confounded by different approaches in consequential modelling, and by differences between attributional and consequential modelling, the comparative analysis is remarkably robust. In relative terms (i.e. in terms of the ranking between glulam beams and steel frames), assumptions in EoL modelling are of low importance. In comparable scenarios (i.e. scenarios with equivalent assumptions), glulam beams have clear environmental benefits compared to steel frames, except for the scenario in which steel frames are recycled and today's average steel production is substituted (ReSub) in

**Table 2** Description of the EoL scenarios

Abbreviation	Energy source in demolition	Fuel in EoL transportation	Means of disposal	Method for handling the allocation problems related to EoL processes	Attr. (A)/ Cons. (C)
Glulam beam scenarios					
IncCut	Diesel	Average	Incineration	Cut-off	A
IncSub	Diesel	Average	Incineration	Substitution of combustion of natural gas	C
GreenIncCut	Wind	RME	Incineration	Cut-off	A
GreenIncSub	Wind	RME	Incineration	Substitution of combustion of municipal biowaste	C
ReCut	Diesel	Average	Recycling	Cut-off	A
ReSub	Diesel	Average	Recycling	Substitution of today's average European production of debarked round wood	C
GreenReCut	Wind	RME	Recycling	Cut-off	A
GreenReSub	Wind	RME	Recycling	Substitution of today's average European production of debarked round wood <sup>a</sup>	C
NoEoL	All impacts of EOL processes are excluded				
Steel frame scenarios					
ReCut	Diesel	Average	Recycling	Cut-off	A
ReSub	Diesel	Average	Recycling	Substitution of today's average European production of low-alloyed steel	C
GreenReCut	Wind	RME	Recycling	Cut-off	A
GreenReSub	Wind	RME	Recycling	Substitution of today's average production of recycled un- and low-alloyed steel	C
NoEoL	All impacts of EoL processes are excluded				

<sup>a</sup> This is the assumed substituted technology also for the “green” scenario, as we see it as a mature technology with limited development potential

which the impact is similar to the comparable glulam beam scenarios. The choice of methodological approach (attributional, consequential or fully disregarding EoL processes) does not seem to influence the relative performance of the compared roof construction elements.

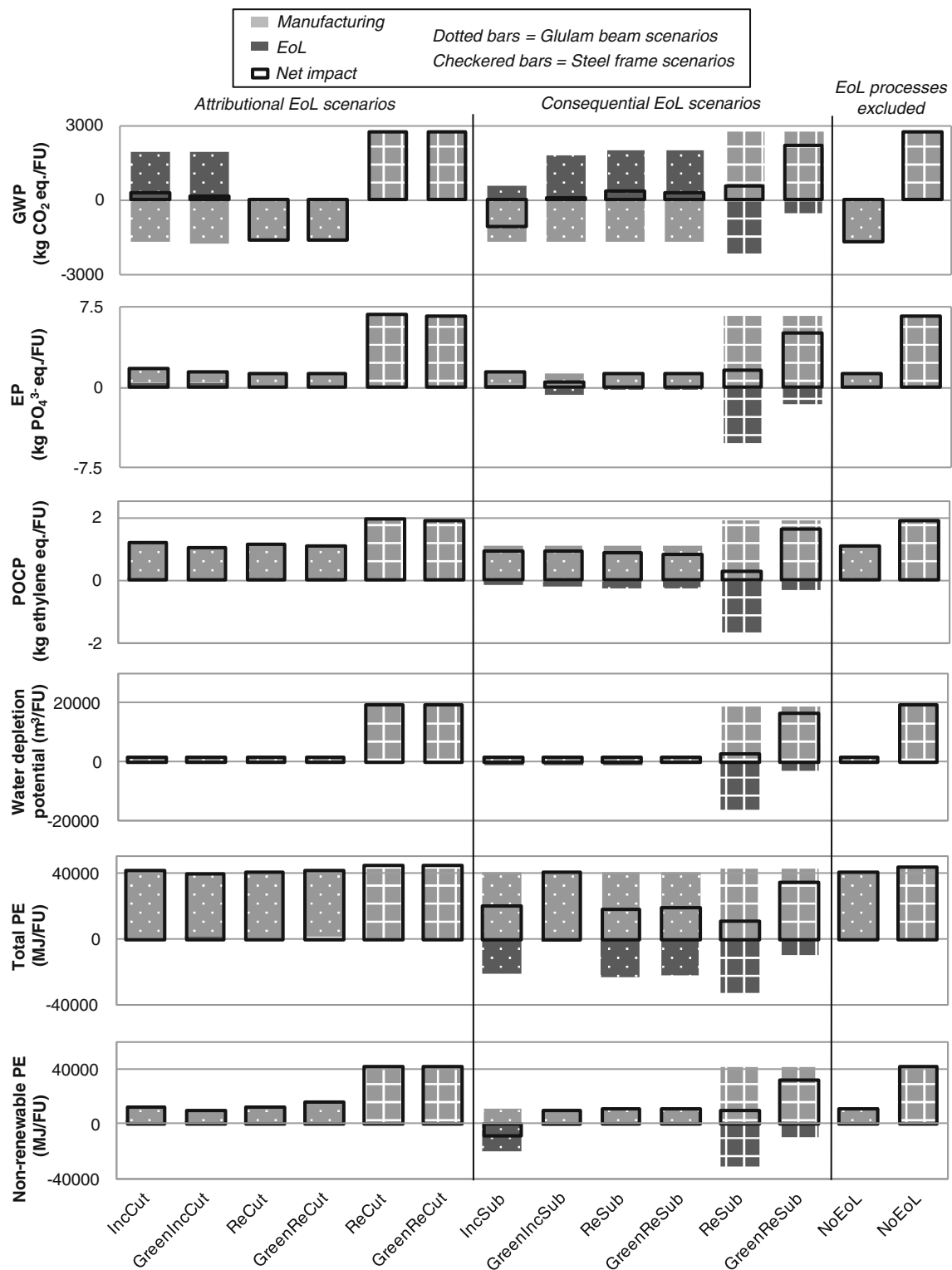
On the other hand, in absolute terms, assumptions in EoL modelling have a significant influence on the studied impact categories. Four factors are particularly crucial: whether EoL phases are considered at all (compare NoEoL scenarios with other scenarios), whether recycling or incineration is assumed in the disposal of glulam beams, whether a consequential (substitution) or attributional (cut-off) approach is used for modelling the disposal processes and whether today's average technology or a low-impact technology is assumed for the substituted technology (compare glulam beam scenarios IncSub with GreenIncSub or steel frame scenarios ReSub with GreenReSub). In contrast, the assumed technologies of demolition and transportation processes are of low importance (compare regular with green cut-off scenarios).

To include a temporal dimension in the mapping of the product system, as done in the present study, offers the possibility to use temporally more dynamic methods for the impact assessment of climate change (for review of methods, see Brandão et al. 2013) and other impact categories. For example, if emissions occurring during EoL processes would be discounted—which under certain circumstances is allowed by the ILCD Handbook (European Commission 2010)—the

GWP scores would be somewhere between the scenario fully excluding EoL processes (NoEoL) and the other scenarios; thus the approach of building cornerstone scenarios does to some extent capture the range of possible outcomes of temporally more dynamic impact assessments.

By accounting for uncertainties in EoL modelling, the present study strengthens the results of other studies that have also found potential environmental benefits of wood compared to alternative construction materials (Bribián et al. 2011; Lippke et al. 2010; Upton et al. 2008; Petersen and Solberg 2005). However, decisions for sustainable development in the construction industry should not solely be based on the impact categories discussed in the present paper but also on the other impact categories recommended in EN 15804 (SIS 2012) and other impact categories of potential importance for wooden materials, for example, related to toxicity or land use. The latter two impact categories are more supply-chain specific than the impacts presented here and are thus difficult to account for in studies on generic European products. Ultimately, decisions will likely depend on the priorities given to different environmental concerns, as also recognised elsewhere (Thiers and Peuportier 2012).

As our results indicate that EoL assumptions can be highly important for LCAs of construction materials—particularly in absolute terms—we recommend that EoL uncertainties are taken into consideration in any LCA of long-lived products. This could, for example, be done as in this study: by



**Fig. 2** LCA results for glulam beams and steel frames in different EoL scenarios in the impact categories of global warming potential, eutrophication potential, photo-chemical oxidation potential, water depletion

potential, total primary energy demand and non-renewable primary energy demand. See Table 2 for a description of the scenario abbreviations

introducing a temporal dimension in the mapping of the product system and using explorative scenarios to test assumptions for processes occurring in a distant and uncertain

future. We chose a 50-year time horizon based on the longevity of the studied constructions. Longer time frames are feasible with the method, but the problem of technological

uncertainty becomes extreme. Furthermore, while straight-line depreciation times of 100 years do exist in financial accounting for long-lived assets, the utility of an analysis that is concerned with future issues typically discounted to zero by decision-makers today is questionable.

For the studied construction materials, EoL modelling should particularly focus on uncertainties regarding the means of disposal, the expected technology development of disposal processes and the type of substituted technology. Also, the choice between attributional and consequential approaches should be treated carefully. It has been recommended earlier that several fundamentally different scenarios are needed when modelling future disposal processes, particularly if a consequential approach with substitution is applied (Mathiesen et al. 2009). Scenarios can also be used to capture the influence of other crucial uncertainties in LCAs of building materials (e.g. as done by Cellura et al. 2011).

More research is warranted to explore other attributional allocation methods (e.g. based on physical or monetary properties) in EoL modelling of long-lived products or to explore what EoL assumptions that are of importance for other construction materials and other long-lived products (e.g. infrastructure such as roads). The proposed research could further clarify when and how EoL assumptions matter and thereby contribute to more robust decision making in the construction sector and potentially also for civil engineering in general. Until now, there has been insufficient consideration of EoL uncertainties of long-lived products, which may hamper sound decision making for sustainable development.

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